A Multiscale Study of Tropical Cyclone Formation, Structure Change, and Predictability in the Western North Pacific Region and TCS08 Experiment Support

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LONG-TERM GOALS AND OBJECTIVES

The overarching objectives of this research project are to obtain an improved understanding of the formation, predictability and structure change of tropical cyclones in the Western Pacific region. These new insights will ultimately improve forecast guidance for U.S. Naval operations in this region.

APPROACH

In recent work the P.I. and two of his collaborators have developed a new paradigm of tropical cyclogenesis that occurs within the critical layer of easterly waves for the Atlantic and East Pacific Basins (Montgomery, Wang & Dunkerton 2010; Dunkerton, Montgomery & Wang 2009). The Kelvin cat's eye within the critical layer of a tropical easterly wave was hypothesized to be important to tropical storm formation because:

H1: Wave breaking or roll-up of the cyclonic vorticity and lower-tropospheric moisture near the critical surface in the lower troposphere provides the moist vorticity region favorable for the aggregation of diabatic vortices and TC formation;

H2: The cat's eye is a region of approximately closed circulation, where air is repeatedly moistened by deep moist convection and protected to some degree from dry air intrusion;

H3: The parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave.

The cyclogenesis sequence is likened to the development of a marsupial infant in its mother's pouch, and for this reason has been dubbed the 'marsupial paradigm.' For the TCS08 field experiment, we have hypothesized that the Marsupial Paradigm may be applicable under certain circumstances in the Western Pacific sector and that easterly waves or other westward propagating disturbances may be important ingredients in the birthing process of typhoons. Our initial analysis of typhoons Man-yi, Nuri, and Hagupit suggests that the paradigm is applicable and should provide useful forecast guidance

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to U.S. Naval operations in this region.

WORK COMPLETED

During the third year of this project multiple cases have been analyzed and a comprehensive review paper on tropical cyclone intensification has been written in support of the Tropical Cyclone Structure 2008 (TCS08) field campaign. Because of space constraints, only a sampling of some of this year's findings will be presented here.

RESULTS

Our multi-scale analyses performed with observational data from Typhoon Hagupit during the pre-depression stage are summarized here to illustrate the research conducted with the TCS08 dataset. The precursor disturbance was initially identifiable as a discrete patch of high moisture in the total precipitable water (TPW) fields on 7 September near 180 E (not shown). No identifiable convective activity was evident in the geostationary satellite imagery, nor any detectable wave structure or vorticity maximum in the global analysis fields. After the TPW anomaly crossed the date line, however, convection began to flare and became trackable in the MTSAT infrared imagery (Figure 1); this disturbance propagated zonally toward the TCS-08 aircraft domain.

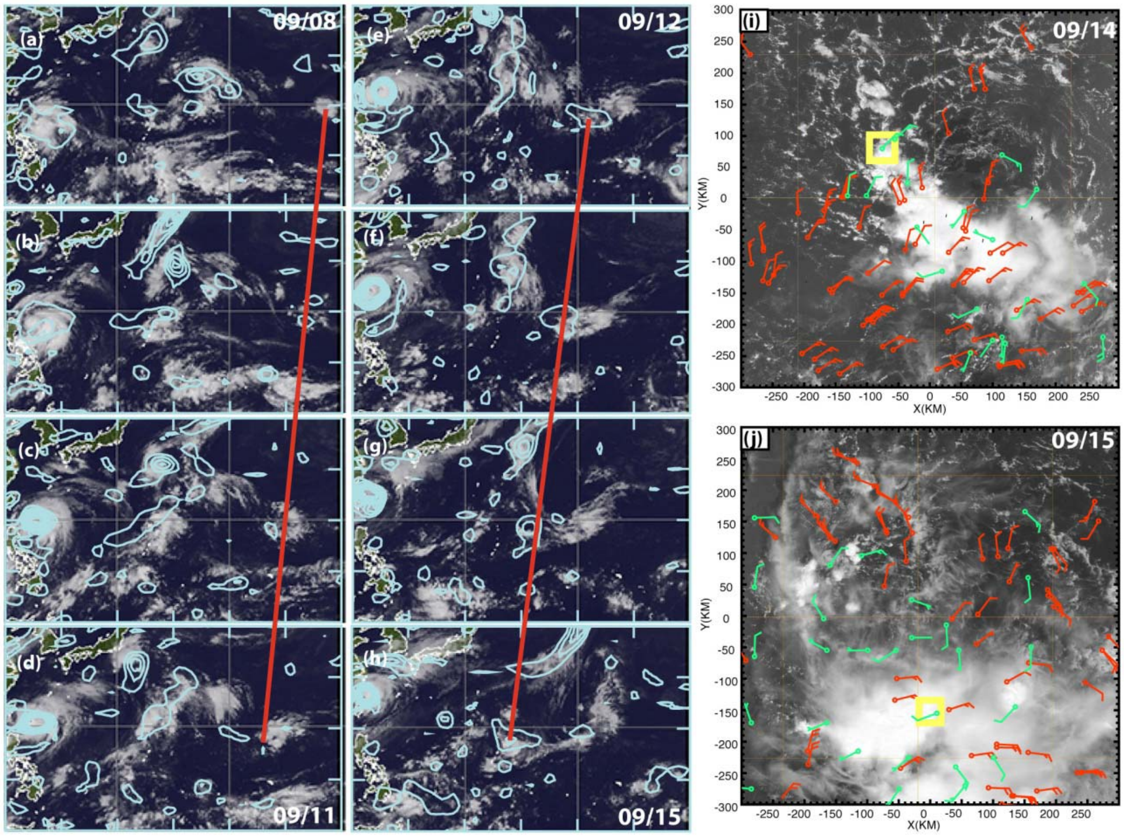

Figure 1. (a) – (h) MTSAT IR imagery at 0030 UTC from 8 – 15 September and 850 hPa relative vorticity from the GFS FNL analysis. Domain is from 0 – 40 N latitude and 120 – 180 E longitude. The red line follows the convective activity associated with the pre-Hagupit disturbance as it propagates westward. Cyan vorticity contours are every $4x10^{-5}$ s^{-1} with a minimum contour value of $2x10^{-5}$ s^{-1}. (i) and (j) Satellite and dropwindsonde composites centered at 18 N and 150 (i) and 148 (j) E on 14 and 15 September. Green wind barbs indicate surface (10 m altitude) winds from dropwindsondes released during the research flights. Red wind barbs indicate atmospheric motion vectors in the 150 – 250 hPa layer at (i) 0057 and (j) 2057 UTC overlaid on visible satellite imagery from the Terra MODIS satellite at (i) 0030 UTC 14 Sep. and (j) 0113 UTC 15 Sep. Yellow boxes indicate aircraft radar analysis locations.

A vorticity maximum at 850 hPa was first apparent in the global model analysis around 00 UTC 09 September; this elevated vorticity anomaly gradually increased in amplitude as the wave moved westward (cyan overlay in Figure 1). The red line in Figure 1 indicates the approximate 4 m s^{-1} westward translation of both the convection and 850 hPa vorticity anomaly that gradually increased in amplitude over time (Fig. 1a – h).

A new variational synthesis procedure called SAMURAI (Spline Analysis at Mesoscale Utilizing Radar and Aircraft Instrumentation) was developed as part of this research project to combine dropsondes, Doppler radar, flight-level data and satellite winds into a comprehensive three-dimensional analysis. The dropsonde winds shown in Figure 1i reveal a weak, closed low-level circulation at the surface in an earth-relative frame at ~00 UTC 14 September 2008, but the circulation is even more evident in a 1 km altitude SAMURAI streamline analysis in the co-moving frame, with a distinct vorticity maximum near the center of the low-level circulation (Figure 2a). A two-plane

mission 24 hours later revealed that the circulation was persistent as the disturbance moved into a lower shear environment and exhibited an increase in convective activity (Figures 1j and 2b). These analyses suggest that Hagupit formed within a local re-circulation region associated with a westward propagating disturbance, similar in some respects to Nuri. The initial mission into pre-depression Hagupit (2008) occurred *four days prior* to the Joint Typhoon Warning Center tropical cyclone formation alert, after which the tropical disturbance went on to intensify into a typhoon causing over 1 billion dollars in damage and 67 deaths.

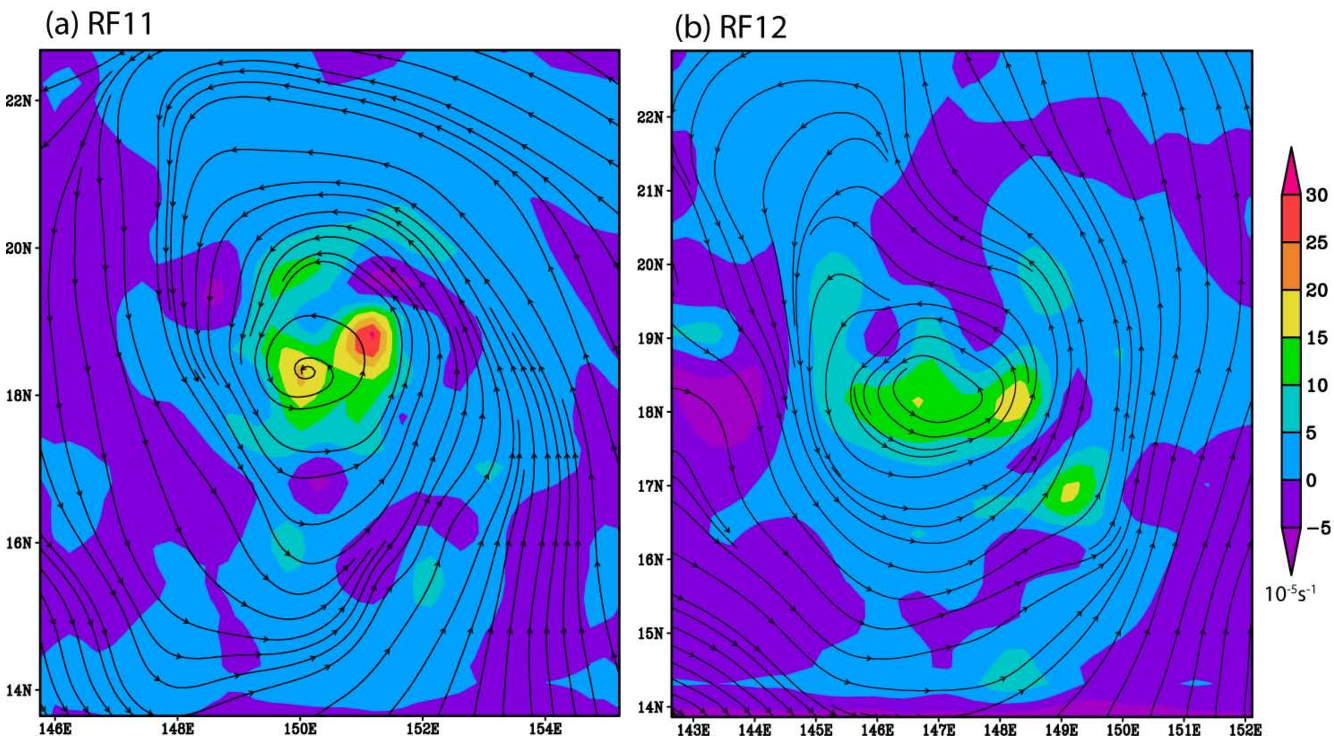

Figure 2. Co-moving streamline and vorticity analysis at 1 km altitude from dropsondes, flight-level, Doppler radar, and satellite winds in pre-depression Hagupit. Reference frame is translating zonally at 4.5 m s^{-1}, centered on 0000 UTC (a) 14 September and (b) 15 September.

ELDORA radar analysis from TCS-08 indicates cyclonic vorticity-rich convective plumes (aka Vortical Hot Towers or VHTs) near the developing cyclonic low-level circulation, lending strong support to the “bottom-up” hypothesis for tropical cyclogenesis. Deep convective structures initiated near the center of the low-level circulation during the first mission provided a unique opportunity for several circumnavigations of a VHT in the pre-depression environment. Analysis of ELDORA data from the boxed region in Figure 1i indicates a quasi-linear organization of shallow and deep convection (Figure 3) near the center of the LLC. Earth-relative winds at 1 km altitude (~900 hPa) indicate northeasterly flow on the northwestern side of the LLC (vectors). Reflectivity exceeding 40 dBZ at 12 km height exists in the deepest convection along the line displaced to the east of the low-level reflectivity maximum (Figure 3b), with a shifting of the winds to stronger northwesterlies aloft. The hodograph (inset in Figure 3b) derived by averaging the radar winds at each level in the 1600 km^2 domain has counter-clockwise turning of the winds with height and an ~11 m s^{-1} northwesterly shear vector from 850 – 200 hPa that is consistent with the satellite wind estimates.

A vertical east-west cross-section through the deep, tilted structure in Figure 3c indicates strong convergence of the low- and mid-level easterly flow at the leading edge of the convective line and an intense, tilted updraft with a maximum vertical velocity of ~25 m s^{-1} at 12 km altitude. This convective structure has a strong, low-level, positive vertical vorticity core up to 6 km altitude (shaded region) that is tilted also, with peak values exceeding $8x10^{-3}s^{-1}$ at 4 km altitude. At 1 km altitude, the $4x10^{-3}s^{-1}$ vorticity is ~100 times greater than the planetary vorticity at this latitude, and an order of magnitude larger than the pre-existing, low-level, cyclonic vorticity on the meso-beta scale (20 – 200 km), estimated at ~$2x10^{-4}s^{-1}$ as shown in Figure 2.

The ELDORA radar analysis from pre depression Hagupit in the western North Pacific offers an unprecedented look at the structure of deep vertical convection in the tropics under the influence of vertical wind shear associated with the ambient and local environmental flow. In some respects, the overall structure of these deep, buoyant, and vortical convective features resemble the VHTs documented in recent idealized numerical simulations of tropical cyclone spin up [Montgomery et al., 2006; Nguyen et al., 2008]. However, their structure is more complex because of the non negligible, environmental vertical shearing flow that tends to tilt the updrafts, contribute additional sources of horizontal vorticity that can be tilted into the vertical, and organize the convection as part of mesoscale linear features [LeMone et al., 1998]. This linear organization is similar to the convective structures observed in previous analyses of tropical depressions [Zipser and Gautier, 1978; Reasor et al., 2005; Houze et al., 2009].

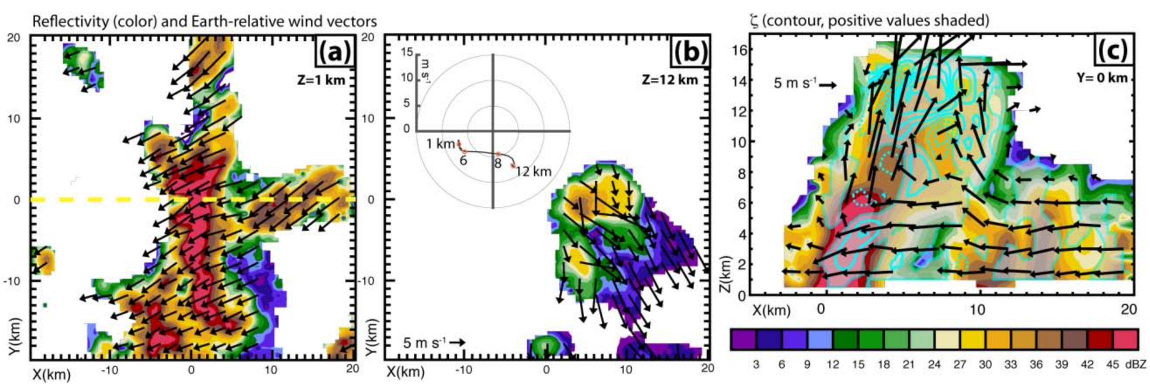

Figure 3. ELDORA analysis from 0036-0058 UTC 14 September, 2008. Horizontal plan view of radar reflectivity (color, dBZ) and wind vectors are shown at (a) 1 km and (b) 12 km altitude. Yellow dashed line in (a) depicts the vertical cross-section in panel (c). Inset in (b) is radar-derived velocity hodograph. Panel (c) shows reflectivity (color), relative vertical vorticity ($4x10^{-3}s^{-1}$ contours, positive [cyclonic] values shaded), and wind vectors in the X-Z plane.

Although the vertical wind shear changed significantly between the two analysis days, and varied also across the disturbance, a consistent juxtaposition of tilted precipitation, vertical vorticity, and updraft columns was apparent. The corroboration of these vortical convective structures within a recirculation region at 18 N latitude, even in the presence of a complex vertically shearing flow, is consistent with the basic tenet that the pre existing low level circulation is enhanced by the coupling of the low level vorticity and convergence in deep convection on the meso gamma scale. On the basis of these observations, together with recent idealized numerical modeling studies suggesting that these convective structures serve as the building blocks for the tropical depression vortex [Nguyen et al., 2008; Montgomery et al., 2010], we hypothesize that repeated convective bursts similar to those

documented here were primarily responsible for the formation of Hagupit as the disturbance moved westward in the western North Pacific. This hypothesis will be tested in ongoing research and the results will be reported in due course.

Formation of Typhoon Nuri:

A first observational and real-time model forecast study of the genesis of Typhoon Nuri during the TCS08 field campaign in the western North Pacific sector was completed and published this year. The analysis and observational data show that the surrounding base state was an easterly trade wind flow and the precursor disturbance to Typhoon Nuri was an easterly wave that originated in the ITCZ in the Central Pacific. This disturbance was tracked more than 10 days prior to tropical storm formation. The dropwindsonde analyses identified the precursor easterly wave disturbance on 16 August and identified an area of weak low-level cyclonic circulation on 17 August.

An overview of the synoptic and dropsonde data for this case has been published by Montgomery et al. (2010) using the newly proposed framework for tropical cyclone formation within the critical layer of an easterly wave. This research is complementary to the work on the formation of Nuri by Dave Raymond, Carlos Lopez and colleagues of New Mexico Tech (Raymond and Lopez 2010). Our analysis suggests that despite propagating through a hostile environment ripe with strong vertical wind shear and relatively dry air, the easterly wave critical layer protected the proto-vortex and allowed it to gestate until it reached a more favorable environment. Within this protective Kelvin cat's eye flow located within the wave's critical layer existed a sweet spot, defined as the intersection between the wave trough and critical latitude, which is the preferred attractor point for tropical cyclogenesis. Global Forecast System Final Analyses and IR satellite imagery, indicate convective bands wrapping around the sweet spot as genesis nears, confirming the hypothesis that this sweet spot is the location where Typhoon Nuri's dominant low-level circulation emerged.

Real-time forecasts were produced using operational global prediction model data to support scientific missions during TCS-08. These forecasts were found to be useful in flight planning discussions and predicted Typhoon Nuri's eventual genesis latitude within 1.5 degrees 72 h in advance. We have applied these forecasting techniques successfully in the summer of 2010 during the National Science Foundation experiment called Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT).

IMPACT

Our first analyses of typhoons Nuri and Hagupit suggests that the new cyclogenesis model is applicable under certain conditions and the model should provide useful forecast guidance to U.S. Naval operations in this region (Lussier 2010, Montgomery et al. 2010, Bell and Montgomery 2010).

A scientific review paper has been written examining the prominent paradigms of tropical cyclone intensification over the past five decades, focusing on a new paradigm articulated in a series of recent papers by ourselves and colleagues. The purpose of this review is to help lay a solid foundation for interpreting the data collected during the intensification and structure change events of storms observed during the 2008 field experiment.

The new intensification paradigm views the intensification process as intrinsically asymmetric and dominated by deep convective vortex structures. These vortical convective structures, or VHTs, exhibit a degree of randomness that has implications for the predictability of asymmetric features of the

developing storm on the convective scale. The VHTs possess local buoyancy relative to the azimuthally-averaged virtual temperature field of the warm-cored vortex, but come under increasing rotational control as the system-scale vortex intensifies.

While a wealth of data was presented in Montgomery et al. (2010) to suggest that the new cyclogenesis model can be a useful forecaster/diagnostic tool in the western North Pacific basin during easterly trade wind regimes, more work remains to be done.

With the development of the SAMURAI analysis package, multi-scale analysis can be conducted that utilize a variety of data sources. Aircraft flight level data, SFMR data, and additional remote sensing data including microwave imagery and ground-based Doppler radar will be used to augment the analysis presented in our first papers and further scrutinize the mesoscale evolution of Typhoon Nuri and Hagupit's tropical cyclogenesis sequences. Planned work includes an examination of the spectrum of convection in pre-depression Hagupit and pre-typhoon Nuri, merger of remnant meso gamma scale convective vortices, diabatically induced convergence as well as frictional influences on the storm scale, and their net impact on the system scale circulation at the meso beta scales. Formal publications will be prepared as our research progresses and reaches maturity.

Using an idealized, three-dimensional, non-hydrostatic numerical model, we have shown that, from an axisymmetric viewpoint, the spin-up of the inner core is associated with the convergence of absolute angular momentum in the boundary layer, where this quantity is not materially conserved. While surface moisture fluxes are required for storm intensification, the intensification does not require the postulated 'evaporation-wind' feedback process that forms the basis of an earlier paradigm. The details of the intensification process as well as the structure of the mature cyclone are found to be sensitive to the boundary layer parameterization used in the model, although they are less sensitive to the surface drag coefficient, contrary to previously published results obtained from axisymmetric balanced models. Balanced and unbalanced contributions to the intensification process are highlighted also.

On the basis of this completed work we advocate further documentation of the lifecycle of VHTs and the way they interact with one another in tropical-depression environments through analyses of existing field data and further field experiments. We see a role also for idealized numerical simulations to complement these observational studies. We advocate also an investigation of the limits of predictability of intensity and intensity change arising from the stochastic nature of the VHTs, which has implications for the utility of assimilating Doppler radar data as a basis for deterministic intensity forecasts.

Finally, a strategy is required to answer the question: what is the "optimum" boundary-layer parameterization for use in numerical models used to forecast tropical- cyclone intensity? The current inability to determine "the optimum scheme" has implications for the predictability of tropical-cyclone intensification using current models.

RELATED PROJECTS

This work is related to the National Science Foundation experiment called Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) conducted in Atlantic basin during the summer of 2010.

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